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EAS age determination from the study of the lateral distribution of charged particles near the shower axis with the ARGO-YBJ experiment

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ABSTRACT

The ARGO-YBJ experiment, a full coverage extensive air shower (EAS) detector located at high altitude (4300 m a.s.l.) in Tibet, China, has smoothly taken data, with very high stability, since November 2007 to the beginning of 2013. The array consisted of a carpet of about 7000 m^2 Resistive Plate Chambers (RPCs) operated in streamer mode and equipped with both digital and analog readout, providing the measurement of particle densities up to few particles per cm^2. The unique detector features (full coverage, readout granularity, wide dynamic range, ..) and location (very high altitude) allowed a detailed study of the lateral density profile of charged particles at ground very close to the shower axis and its description by a proper lateral distribution function (LDF). In particular, the information collected in the first 10 m from the shower axis have been shown to provide a very effective tool for the determination

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of the shower development stage ("age") in the energy range 50 TeV - 10 PeV. The sensitivity of the age parameter to the mass composition of primary Cosmic Rays is also discussed.

1. Introduction

The energy spectrum and composition in the so-called knee region (10^{14}-10^{16} eV) could be crucial to understand the origin and acceleration mechanism of the very high energy cosmic ray (CR) flux, which are among the main open problems in particle astrophysics. The detailed study of several features (longitudinal structure, lateral distribution of charged component at detection level, size, etc.) of extensive air showers (EAS), produced by these particles in our atmosphere and detected by surface apparata using different techniques, is the primary tool for obtaining information about CR primaries when direct measurements are prevented by the too low fluxes.

The shower development stage in the atmosphere, is expressed by the so-called *longitudinal age*, which essentially reflects the height of the shower maximum with respect to the observation level. When measured at a fixed altitude (the detection one), it depends on the energy of the interacting primary particle, while, for fixed energy, it depends on the primary nature. Indeed, heavier primaries interact higher in the atmosphere and moreover, according to the superposition principle, they act like a number (equal to A, the nucleus mass number) of nucleons, each one generating and independent shower at the same height on average (since each nucleon carries out the same fraction of the nucleus tottal energy). The result is that heavy primary nuclei produce showers that, on average, reach their maximum size at a greater distance from the detector than a lighter primary of the same energy. For this reason, the combined use of shower energy and age estimations can ensure the sensitivity to the primary nature.

An EAS array by itself cannot measure directly the shower development stage, through the determination of the depth of the shower maximum, $X_{\max}$ (as made for instance by fluorescence detectors). It can only measure the particle density distribution at ground as a function of the core distance (described through a lateral density function, LDF) and from the slope of this distribution get information on the longitudinal shower development. In fact, the detailed study of the lateral particle density profile at ground is expected to provide information on the longitudinal profile of the showers in the atmosphere, that is to estimate their development stage, or *age*. The relation between the lateral shape of the detected particle distribution and the shower age is quickly explained. Showers starting high in the atmosphere show a flat lateral particle distribution, mainly due to multiple scattering processes. Such showers, characterised by a large value of the age parameter, are called *old*. On the contrary, *young* showers have started deeper in the atmosphere, thus having their maximum closer to the observation level. This results in a steeper lateral particle distribution, which corresponds to a smaller value of the age parameter. Apart from fluctuations, the height of the shower maximum depends on energy and mass of the initiating particle. Therefore, the lateral shape parameter is also sensitive to the mass of the CR primary.

Historically, it was shown that such lateral distribution (at least of the e.m. part of the shower), as measured by a traditional sampling EAS array at distances of the order of hundred meters from the core, can be properly described by a LDF like the Nishimura-Kamata-Greisen (*NKG*) structure function [1,2], with parameters depending on the shower size, the detection altitude and the shower age. The age parameter determined in this way is usually referred to as *lateral age* [3,4], since it is obtained from the LDF. It, in principle, coincides with the longitudinal age in particular for purely e.m. showers, but they can in fact differ, since most showers come from hadrons and the two quantities are measured with completely different techniques. However, they are expected to be strongly related. Moreover, as experimentally observed, the *NKG* function with a single lateral age parameter is frequently inadequate to properly describe the lateral density distribution of EAS charged particles at all distances. This implies that such parameter changes with the radial distance and, for this reason, the concept of *local shower age parameter* was introduced [5] to denote essentially the lateral age at each point. As a consequence, any use of the lateral age parameter in order to infer the shower development stage in the atmosphere has necessarily to face that problem. To this aim, a full MC simulation of both the shower transportation in the atmosphere and the detailed detector response is needed.

In this paper we show how the peculiar features of the ARGO-YBJ detector can be exploited to study the distribution of charged particles in the region around the shower axis by describing its lateral profile by means of a proper LDF, thus obtaining an estimation of the shower development stage through the local age parameter. We also demonstrate and discuss the sensitivity of such age parameter to the masses of the shower initiating primaries.

2. The ARGO-YBJ experiment

The ARGO-YBJ detector was a full coverage extensive air shower (EAS) array made by a single layer of Resistive Plate Chambers (RPCs) operated in streamer mode, for γ-astronomy observations with $\sim$ 100 GeV energy threshold, search of Gamma Ray Bursts in the full GeV/TeV energy range and CR studies in the energy range (1-10^4) TeV [6]. For these purposes, the array was installed in the Cosmic Ray Observatory of YanBaJing (Tibet, China), at an altitude of 4300 m above sea level (corresponding to a vertical atmospheric depth of about 606 g/cm^2), and ran in its full configuration since November 2007 until February 2013. It was organized in 153 clusters of 12 RPCs each. Any single RPC was read out by ten 62 $\times$ 56 cm^2 pads, which were further divided into 8 strips, thus providing a larger particle counting dynamic range [7,8]. The signals coming from all the strips of a given pad were sent to the same channel of a multi-hit TDC. The whole system provided a single hit (pad) time resolution of $\sim$ 1.8 ns, which, joined to the full coverage feature, allowed a complete and detailed three-dimensional reconstruction of the shower front with unprecedented space-time resolution. A system for the RPC analog charge readout [9] from larger pads, each one covering half a chamber (the so called *big pads*, BP), has also been implemented and took data since January 2010. This actually extended the detector sensitivity range from about 10^{14} eV up to about 10^{16} eV of the primary energy. The analog readout system has been operated with different gain scales (from G0 to G7, with increasing gains), which determined the threshold and the maximum number of particles that could be reliably measured by each BP. The highest gain scale G7 allowed low density values to be measured down to few particles per m^2, overlapping its dynamic range with the detector operated in 'digital mode', i.e. simply counting the number of fired strips, that saturates at about 20/m^2. The data collected by this scale were mainly used for calibration purposes, following the procedure described in [9]. The other scales had decreasing gains